16 Telemetry Systems: Phone, Radio, Cellular, and Satellite

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INTRODUCTION

Telemetry is a specialized form of communication that converts a measured parameter into a representative electrical signal, transmits it to a distant location, and reconstructs it into a quantitative value. Telemetry systems communicate a relatively small amount of data over distances greater than one-quarter mile to multiple sites using limited bandwidth, eliminating the need for operators to be located at, or periodically visit, the remote sites. Because of this, in process control applications they offer fast response and save a great deal of time.

The telemetry communication channel can use wires or free space to transmit information. Since cabling (e.g., copper or fiber optic) is generally the most expensive part of a communications link, wireless technologies are often a less expensive alternative. Wireless telemetry is a radio technology such as licensed radio, unlicensed radio, cellular, or satellite.

Telemetry systems are found in many industries including

- Electrical utilities (e.g., automatic meter reading)
- Water and wastewater utilities (e.g., pump stations, tank levels, automatic meter reading)
- Oil and gas pipelines
- Aerospace (e.g., rockets, satellites)
- Security systems (e.g., alarms)
- Race cars
- Meteorology and hydrologic data (e.g., weather stations, stream gauging, water quality, and weather balloons)

Telemetry systems are specialized communication networks that bring field data back to a central location. Because only a limited amount of data is required, these systems are characterized by low bandwidth. When telemetry systems are used for remote control, the speed of response and repeatability become very important and near real-time response may be needed. Although abundant bandwidth can be used to assure response time, deterministic protocols enable time-sensitive data to be sent while using limited bandwidth.

Telemetry is designed to use dedicated channels though it can also use general purpose channels. Telemetry systems provide long-range reach on a single device outside the fence line of the plant, from less than a mile to several hundred miles away. Industrial telemetry systems are designed for harsh environments with extremes in temperature, vibration, and corrosive conditions.

The institute of electrical and electronics engineers (IEEE) 802 wireless technologies, like Wi-Fi, Bluetooth, and ZigBee, normally communicate within the immediate vicinity and are designed for use in office settings.

TELEMETRY AND NETWORKS

Types of Telemetry

There are two main uses of telemetry systems: *data acquisition* and *remote control*.

Data acquisition is used to collect data from a remote site. Often, this is not a time-critical task as long as the data arrive intact. In this type of system, most of the data flow from the field to a central location. Time stamping of the data samples is used so that if delays occur during transmission, the data values can be put in the correct order. Losing any data value is problematic.

Remote control and supervisory control and data acquisition (SCADA) systems have different needs. In SCADA systems, the information is time sensitive; the current value is most important, and data that are even 1 min old may not be of much use. In this situation, a system that can rapidly deliver data is ideal, even if it occasionally loses a value.

Modes of Communications

Every communication channel consists of combinations of transmitters and receivers. There are three different modes that characterize a communication channel: *simplex*, *half duplex*, and *full duplex*.

Simplex mode is the simplest mode. It is a broadcasting mode where sites blindly transmit and a single central receiver listens. One of the advantages of this mode is that remote sites do not need receivers and the central location does not need a transmitter. This mode is generally associated with report by exception polling.

Half duplex channel is able to transmit and receive on each end, but because there is only a single circuit or channel, only one party can talk at a time. This functionality is like a push-to-talk radio or cell phone.

Full duplex channel enables both parties to talk at the same time without interference. It usually consists of two separate circuits (e.g., phone) or two separate channels (e.g., radio).

Half and full duplex modes improve reliability compared to a simplex mode because an acknowledgement of the data is possible. If the acknowledgement is missing, the data can be sent again. In a simplex system, there is no indication of whether the data reached its destination. Because of this, it is common to send data more than once to improve the chances of reception.

Telemetry Topologies

Topology describes how the different parts of a system are physically connected.

Point-to-point system connects each remote site to a central location using a separate circuit or channel (Figure 16.1).

Point-to-multipoint system connects several remote sites to a central location (Figure 16.2). The central location sends a message to all remote sites at the same time. Each remote site has a unique address and only one remote site responds to the central location's request. This is controlled by protocol implemented either in the interface device or in the software.

It is important to note that topologies occur both at the physical level and at the protocol level. A point-to-point connection often uses a point-to-multipoint protocol. A peer-to-peer network can be used to execute a master–slave protocol as well.

Polling is used for point-to-multipoint systems; it incorporates the idea of a destination station number to differentiate between remote sites.

Master–Slave Polling

Master–slave polling is widely used in duplex systems. It is not possible to use this on a simplex system because no means exist for the central site to transmit to the remote sites. Popular protocols that support master-slave polling are Modbus and DNP3 (distributed network protocol). The central location sends a message addressed to a single site to all the remote sites. Only the remote terminal unit (RTU) that matches the address responds. The message is checked for errors and if it is not totally correct, the central location polls the remote site again so that the message is re-sent. If there is no response, the central location will try again up to the maximum retries allowed, which is usually set to three. The central location will then poll the next RTU in sequence.

This protocol avoids contention and interference by controlling the system so that only one RTU talks at a time. The protocol also provides a positive confirmation that the RTU is operating.

A limitation of this protocol is that delays increase proportionately to the number of RTUs in the system. Once a site is polled, it is not polled again until all the other sites have been polled. In a large system, this can easily exceed 60 s.

Improvements to basic master-slave polling can be made in several ways:

- Segment the system into separate areas served by different master radios
- Prioritize site polling for critical sites
- Interrupt polling to service user commands
- Use a short status poll to check if no changes occurred since last poll
- Use higher data rates

Report by Exception Polling When master-slave systems become very large, the time to poll all sites in the system becomes excessive. Reporting by exception can reduce the communications traffic by 50–100 times, but each node must be able to act as a part-time master. When field changes are

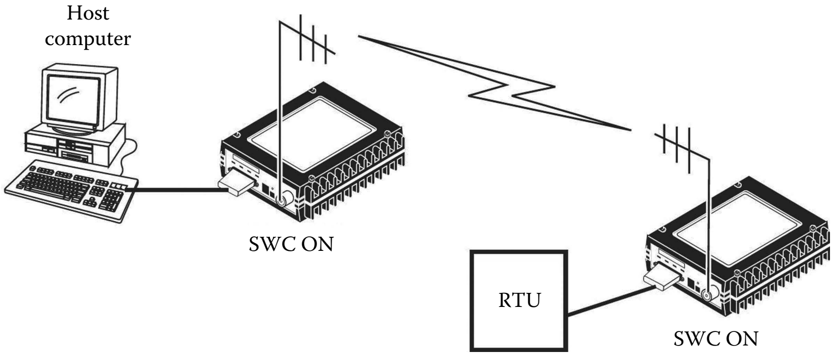

FIG. 16.1
Typical point-to-point link. (Courtesy of General Electric, Fairfield, CT.)

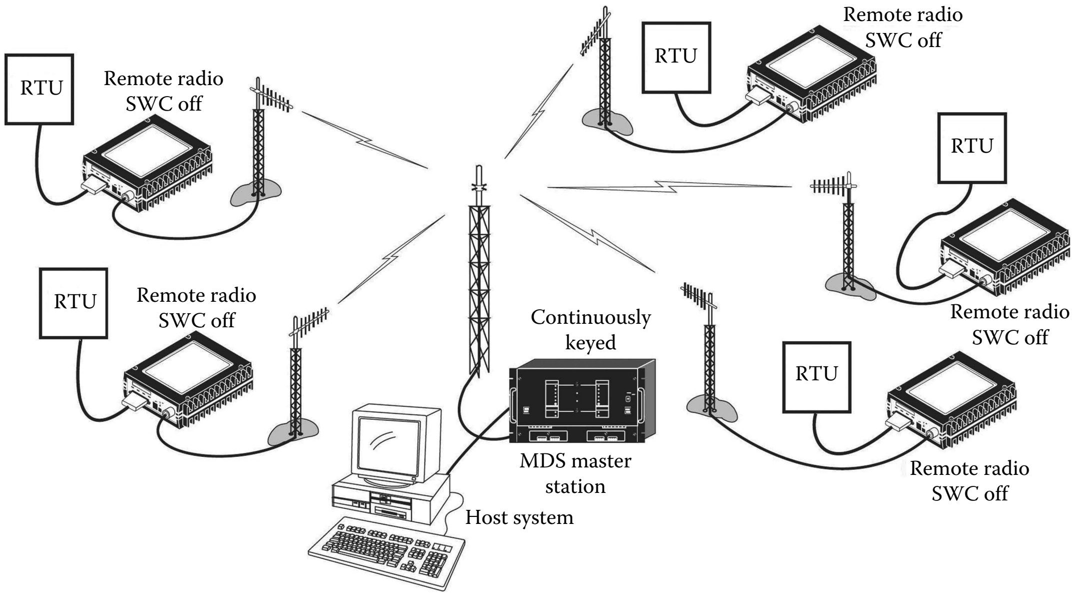

FIG. 16.2
Typical MAS network. (Courtesy of General Electric, Fairfield, CT.)

sensed, the RTU transmits to the central unit in either mode. If two or more RTUs transmit at the same time, the messages will be lost.

The simplest systems are simplex, which use a single transmitter at each remote location and a single receiver at the central hub. In a simplex system, this is strictly one way and the RTU cannot tell if the message was ever received. To improve the likelihood of the message getting through, RTUs will often be configured to transmit the same message several times at random intervals, which makes interference much less likely. The central site cannot detect if a remote site is not sending information because of equipment problems.

In a duplex system, an acknowledgement can be sent from the central site confirming reception. If a confirmation is not received, the RTUs will transmit the same message up to the maximum number of retries set up for that site. The remote sites can monitor the channel to verify that no other transmitters are operating before attempting to send data.

Report by Exception with Integrity Poll In a large system, the problem of determining non-transmitting sites while still optimizing the response of the system is solved by using report by exception with integrity poll; this requires more sophistication than the other techniques referenced earlier. Like master-slave polling, only duplex systems can be used. Popular protocols that support this are DNP. For most of the time, this system operates as a report by exception polling system.

Periodically, the system polls all sites to verify that they can respond and to get a fresh update of the current site data. Sites that are not transmitting are alarmed.

Peer-to-Peer Communications

Peer-to-peer networks offer the most flexibility, but are the most complicated system, requiring the use of packetized data.

In a peer-to-peer topology, any station can send a message to any other station. Also called a mesh or packet system, this usually requires the buffering of messages in transit and routing decisions so a smart device is used. It is common to have most sites in this type of network configured as store and forward repeaters. The transmission control protocol/Internet protocol (TCP/IP) is a peer-to-peer example. Using the proper protocol, a virtual point-to-point or point-to-multipoint network can be constructed within a peer-to-peer network.

Telemetry Protocols

Most protocols designed for telemetry or real-time control are based on small data blocks. Small data blocks are more likely to get through the first time without retries. Larger data blocks reduce overhead and offer increased speed but are slowed down if retries are needed.

Serial protocols play an important role in telemetry systems. Modbus is a serial protocol that has become a de facto industry standard. Modbus has two major variants: Modbus RTU and Modbus ASCII (American standard code for information interchange). DNP has also become very prevalent in the industry, especially outside of the United States. Many manufacturers have serial protocols, most of which handle messages as packets of information, not just individual characters. The frame arrangement generally follows the sequence of source, destination data length, data block, and cyclic redundancy check (CRC). When these are passed to a modem, the character-by-character parity check may be done at the serial port, but this is often ignored because the CRC and block check character (BCC) are much better at detecting errors in the data block.

Many radios offer an Ethernet port that can be used to transmit any Ethernet-based protocols. Using a terminal server, serial protocols can be converted to IP for transport over Ethernet devices. One disadvantage is the additional IP information that is wrapped around the original protocol can become a large percentage of the transmitted information. This can have a large impact on systems that charge for usage on a per-bit basis.

Some radios offer both a serial port and an Ethernet port. However, be careful not to connect Modbus IP on one end and expect Modbus RTU to appear on the serial port at the other end. Modbus IP will appear on the Ethernet port unless imbedded Modbus IP to Modbus RTU conversion is specifically offered by the manufacturer. Some radio models offer an imbedded terminal server to easily make this type of conversion.

There are four main mediums that are used in telemetry:

1. Telephones
2. Radios
3. Cellular networks
4. Satellites

Each of these is covered in detail in the following paragraphs.

TELEPHONE TELEMETRY

Although a simple pair of wires can be used to transmit telemetry, they can do so only for short distances because of signal loss. Each signal requires another pair of wires. Individual copper pairs become expensive to install and maintain as the distance and number of signals increase. Telegraph was one of the first widespread electric technologies to disseminate information over significant distances because it overcame these obstacles. Telephone evolved from telegraph. Leasing telephone lines is a practical solution for voice and data transmission.

Analog Leased Lines

Leased lines are available in two-wire and four-wire circuit configurations. A two-wire leased line is the telephone company's version of a wired pair. Telephone company leased lines provide a dedicated communications link between two or more sites; some are available as dry pairs, which are not energized while others carry typical phone company voltages. Unlike dial-up lines, no dial tone is provided since the circuits are permanently connected. A leased line connects the central location to the nearest phone company central office (CO). At the CO, the leased line is connected to another pair of wires that lead to the end site.

A four-wire leased line is normally used in multi-drop systems but can be used point to point. This line consists of two pairs, one for the central location and one for the remote sites.

Serial modems are available in two-wire leased line, four-wire leased line, and dial-up versions. Most dial-up modems can be used on two-wire leased lines, but four-wire modems must be used on four-wire leased lines.

Analog Leased Lines Topologies

Point-to-Point Analog leased lines are point-to-point systems by design. The leased line runs from the remote site to the central through a CO to the central site. Modems are placed on each end for a complete communication channel. In a point-to-point configuration, four-wire leased lines are set up just like two-wire leased lines.

Point-to-Multipoint In a multi-drop configuration, a four-wire leased line is like a party line—every site can hear and talk to every other site. The central location is connected to all the sites through the CO; this is called bridging. One of the two pairs in a four-wire circuit is used for the master to initiate a command that all the end sites can hear. Only the end site that is addressed responds on the other pair, while all the other sites remain quiet. The coordination between the end sites is critical so that two sites do not transmit at the same time, resulting in no communication at all since the individual messages jumble together. To avoid this conflict, the site communication is usually controlled using a serial protocol.

Although it requires additional effort, two-wire leased lines can be configured to communicate with multiple remote sites by connecting multiple circuits together at the central location instead of the CO. All modems at the central location can be joined together at their serial ports using a serial port sharer as the bridging device. However, this configuration tends to be more costly than using four-wire leased lines because each line to every remote site and their associated modems are needed at the central site. For example, if there are 10 remote sites, one modem will be needed at each site and 10 modems will be needed at the central site, totaling 20 modems. An equivalent four-wire system would only require 11 modems, one at each remote site and one at the central. A four-wire leased line is usually a better alternative for multi-drop topologies.

Analog leased lines have become more difficult to obtain in many areas because phone companies are transitioning to digital circuits.

Dial-Up Line

Regular voice phone service or dial-up is a switched circuit technology. Regular phone service and modems can be purchased and used to construct a telemetry system. The phone lines and off-the-shelf computer modems must be ordered and installed at each site, including the central site. A controller can be used to dial the connecting number from the central location or the modem can be configured to automatically dial the end site if the connection is lost.

A disadvantage of dial-up is that when the central location uses the same line to call multiple sites, a delay in communications occurs each time to set up the call. These systems also pose a security risk from outsiders. A rouge computer using voice over IP (VOIP) can be used to dial a wide number of phone numbers to find active modem connections, allowing a perpetrator access into the system.

Dial-Up Topologies

Point-to-Point Dial-up phone service is a one-to-one system. For every line and modem at a remote site, its counterpart is in the central location (e.g., if there are 20 sites, there will be 20 modems at the central location). This arrangement provides good performance because the connection is almost always present. Modem dialing, disconnect time, and negotiation are eliminated, which provides a faster system. However, the monthly fees for each of these lines quickly add up. The modems may be set up to automatically redial the site number if the connection is lost.

Point-to-Multipoint Another configuration is to have a central polling modem call each site in sequence, exchange data, and then hang up before calling the next site. This saves the expense of phone lines because only one line is needed at the central location but is offset by lower performance due to the time required to set up each call.

Peer-to-Peer This is difficult to set up with analog phone lines.

Digital Phone Services

Phone companies are now offering digital services to supplement voice services. Many different types of digital lines are available and are often configured as part of a wide area network. A few of these are of interest in telemetry applications. Private lines include digital data service (DDS) and frame relay. The best known Internet connection is an asymmetrical digital subscriber line, so called because download and upload speeds are different. This service usually provides Internet service to residential end users and small businesses. A virtual private network connection is recommended if sending system data over the Internet.

DDS A DDS line provides a private dedicated digital link between two or more sites that is permanent and available at all times, offering the flexibility of point-to-point or point-to-multipoint configurations. Information is transmitted end-to-end in a digital format, which improves the error rate. Data speed is measured in bits per second (bps). DDS provides fixed transmission speed choices of 2.4, 4.8, 9.6, 19.2, and 56 kbps. Bridging is required to connect multiple sites to the same host.

Frame Relay A frame relay line uses the phone company internal network (not the Internet) to transport data packets. Because of this, defined network paths, called permanent virtual circuits, can be set up between sites. This offers a significant security advantage since data are never exposed directly to the Internet.

Frame relay is a packet framework that works with other digital technologies. Instead of having a full-time digital connection between each point and the central location, frame relay uses the phone company's internal network, known as the cloud, to direct data packets to their destinations. This internal routing equipment is shared between all users so there is no guarantee that a path will be available through the cloud. Sending data to multiple destinations is also able to be configured; this can be useful if a backup location is needed in case the primary location is out of service.

Frame relay does not provide error checking and is protocol independent. Data are encapsulated by the frame relay equipment, not the network. Frame relay is entirely digital, which reduces the chance of error and offers excellent transmission rates, operating from 56 kbps to 1.544 Mbps. Frame relay sends information in packets called frames through a shared relay network. Each frame contains all the information necessary to be routed to the correct destination. In effect, each end point can communicate with many destinations over one access link to the network. Frame relay offers a committed information rate, which is the minimum speed at which data will be transmitted.

Frame routers or frame relay assemblers/disassemblers (FRADs) are used at each site and typically connect to an Ethernet router or bridge. Separate routing equipment for multiple sites is not required. In a multipoint topology, the host site is usually provided with a greater bandwidth connection than the end sites.

Digital Phone Service Topologies

Digital lines are peer-to-peer by design since they rely on packetized data. Each remote site connects to the phone company. A phone company router directs the packet to the correct line to deliver it to its destination. Any remote can initiate a message. Using the proper protocol, a virtual point-to-point or point-to-multipoint network can be constructed.

RADIO TELEMETRY

Like the transition of telegraph to telephone, radio started using Morse code and developed into a voice medium. As more users adopted radio technology, the equitable allocation of frequency use became necessary. The International Telecommunication Union (ITU) was founded in 1932

TABLE 16.1
Frequencies Used for Data Telemetry

Frequency Band	*Licensed/Unlicensed*	*Type*	*Data Rate*
150–174 MHz	Licensed	Splinter channels	9.6 kbps
450–470 MHz	Licensed	Offset frequency	9.6 kbps
800 MHz	Licensed	Trunked	4.8 kbps
902–928 MHz	Unlicensed	Spread spectrum	19.2 kbps
928/952 and 932/941 MHz	Licensed	MAS	9.6 kbps
960 MHz	Licensed	Point-to-point	768 kbps
2.4–2.4855 GHz	Unlicensed	Spread spectrum	1.544 Mbps
5.725–5.85 GHz	Unlicensed	Spread spectrum	1.544 Mbps

to coordinate radio use worldwide and became a United Nations-specialized agency in 1949. In 1992, the ITU reorganized into three sectors; the sector that focuses on radio is now the International Telecommunication Union Radiocommunication sector (ITU-R).

In the United States, two government agencies control the allocation of radio spectrum: the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). The FCC balances public and commercial use of the airwaves and regulates the allocation of radio frequencies and locations to nongovernment users to avoid interference between licensed users. The NTIA, created in 1978, coordinates radio spectrum used by the U.S. government in cooperation with the FCC. Several telemetry bands are available. Frequencies used for data transmission are listed in Table 16.1.

Radio Modems

Radio modems are similar to telephone modems. They translate serial data into tones that can be transmitted by the radio. These modems generally support serial (RS-232) and/or Ethernet protocols. Serial protocols that rely on quiet time to signal the end of a message (similar to Modbus RTU) need to be special buffering in the radio. Otherwise, a delay in transmission can cause the messages to be split into multiple pieces and the receiver will not be able to recognize it as a valid message.

Simple Radio Modems Radio frequency (RF) or radio modems typically transmit data from 9.6 to 19.2 kbps. Radio noise and interference can corrupt data during transmission. In addition, some radio modems suffer from a condition called squelch tail, which is caused by a burst of noise when an RF carrier is lost, causing the receiver to misinterpret the burst of noise as data.

Parity is the most basic error check in serial communications. In a parity system, a parity bit is added to the 8 data bits to make a 9 bit word. Parity determines if the binary sum of bits in data should be even or odd. In an even parity scheme, if the first 8 bits are an odd sum, the parity bit is set to make the sum even. If the first 8 bit sum is even, then the parity bit is set to zero so that 9 bit sum is even. The parity calculation is done when data are received; if it is even, no error is detected. If one of the bits changes during transmission, the parity will become odd and the parity check will fail. If the parity check fails, the data are usually requested again. Parity is a word-based check, it is simple to implement and does not require buffering.

Serial protocols like Modbus and DNP3 implement more sophisticated error checking. A fixed number of data words are buffered and a calculation is performed that yields a CRC or BCC value. If those checks fail, the block of data must be re-sent. Most of the time, this check is performed in the end equipment instead of the radio. Very few errors, even if multiple bits are changed, will pass this test.

Intelligent Modems A digital radio has a built-in modem and often has a microprocessor for error checking and data buffering. Buffering is especially important for time-based protocols like Modbus RTU. By default, spread spectrum radios are intelligent because a microprocessor is needed to coordinate hopping. Digital signal processing (DSP) is used to emulate primary modulation, demodulation, intermediate frequency filtering, and communications port functions. This improves consistency and replaces the analog components that would otherwise be required.

Packet Radio Packet radio grew out of the U.S. Department of Defense Advanced Research Projects Agency in the late 1960s. Amateur radio started using it in 1978. Some devices offer the ability to packetize in the radio without needing a separate controller. Packet radio technology is transparent to the data stream.

As the serial data are received at the packet radio, it is stored in an internal data buffer as a data frame. Full buffering of data is a side benefit of this technology. Data flow control must be implemented so that the data stream is interrupted when the buffer is full. Data are assembled into blocks of 128–256 bytes. Serial control bits (i.e., start, stop, and parity) are not included.

CRC or BCC values are calculated for the block of data and added onto the end for error checking at the receiver. This provides auto error detection, which is better than parity alone. A destination address (1–255) is added to the front of the packet. Contention resolution uses carrier sense multiple access (CSMA). The packet is then transmitted.

If a packet is received by a radio that is not the ultimate destination, one of two things occurs. If the radio is a repeater that is set up to forward messages and the received data are good, the packet is retransmitted when the channel becomes quiet. If the radio is not a repeater, then the received packet is ignored.

If a packet is received at the destination radio, and it is good, a positive acknowledgement is sent back to the sender to confirm reception. Using this scheme, up to 255 stations can share the same radio channel.

Licensed Bands

The FCC licenses fixed channels and permits higher output power than unlicensed bands. The FCC allows 12.5 kHz channels with data rate of 19.2 kbps. A radio license offers protection and provides recourse against radio interference originating from other users. Frequency coordinators control pools of frequencies in a geographic area for classes of service and industry. Once the frequency is assigned, the application is forwarded to the FCC. Temporary licenses may be available.

When a prospective user applies for a new frequency, the FCC considers the proposed use and whether the frequency is already in use by a nearby user to avoid interference. Since frequency congestion is a significant problem in metropolitan areas, the FCC has opened new frequencies between channels and is encouraging narrower bandwidths to permit more users to operate in a given area.

The typical bandwidth of very high frequency (VHF) and ultrahigh frequency (UHF) channels is 5 kHz, which is similar to the voice range of 300–3000 Hz. On any given channel, only one transmitter can be active at a time to avoid interference, unless the transmitters are far enough apart. For this reason, radio transmitters are not run continuously and multiple users can use the same channel as long as they are distant from one another.

New license applicants often use the services of a radio consultant, who research open channels, user types, bandwidth needs, frequency, field tests, and proximity to other users. With a fixed bandwidth per channel, only a finite number of channels can fit in a given radio band, especially since some space is needed between channels to avoid interchannel interference. In metropolitan areas, channels can be in short supply. Splinter frequencies and offset channels are available in some bands for telemetry use between regular voice channels.

VHF 150–174 MHz Lower frequencies allow transmission over longer distances than higher frequencies, especially over rough terrain. However, background noise is higher than UHF. VHF is primarily used for voice, and open frequencies are scarce.

Splinter channel spacing is 7.5 kHz between main channels, with 14 splinter channels available for telemetry. The maximum transmitter output power in this band is 30 W. Antenna towers are restricted to less than 200 ft. Communication rates are typically between 300 and 600 bps. This band is very crowded with primary voice users; no repeater pairs are available.

UHF 450–470 MHz This band has both main channel (voice primary) users and offset channel (secondary) users. The main channels permit operation of up to 30 W with a 0 decibel (dB) central antenna but it is hard to get a clear license. The main channel spacing is 12.5 KHz.

Offset channels are secondary and are located 6.25 kHz between the main voice channels. These channels may suffer interference to adjacent main voice channels, which are primary. Many offset channels are available and multiple channels can be licensed. Repeaters are allowed and pairs of frequencies are available. Data speeds are typically up to 9.6 kbps. Transmitting power is limited to 2 W; transmitting antenna heights are limited to 20 ft. Foliage starts to become a problem at this frequency.

800 MHz Trunking and Specialized Mobile Radio Trunked radio systems are primarily voice systems; they use 15 W radios and have no antenna height limits. Channel availability can become limited, especially during emergencies. Trunking radio uses multiple channels and unit identification (ID) numbers. The system controller identifies an open channel, contacts remote locations, and directs them to the open channel. Groups of users can be assigned their own channels. The system optimizes frequency use and is able to be easily reconfigured, enabling it to assign priorities to group emergency personnel. Three different addresses are assigned to each radio: universal address, group address, and discrete address. Group broadcast is possible. The system controller constantly handles channel assignments.

Data usually have a low priority on these systems, with data rates up to 4.8 kbps. Access time is typically 1 s. System polling and response times are not deterministic and can vary considerably.

These systems have good coverage with a moderate transmitter power of 15 W. Data can be added to an existing voice system without interference. The system works better if some channels are set aside for data use.

Channel availability may be reduced during local events, such as flash floods or hurricanes. There are multiple users with priority access including rescue, police, and fire while data transmission generally gets low priority.

928/950 and 932/941 MHz Multiple Address Systems The FCC has allocated dedicated RF channels for point-to-multipoint systems. The multiple address system (MAS) radios are configured in a point-to-multipoint arrangement only. Transmission can be used for two-way (interrogate/response) communications between a master station and its remote sites.

MAS licenses were originally only available in the 928/952 MHz band, but FCC frequency re-farming created a new set of frequencies by the addition of the 932/941 MHz band in 2001. There are a total of 160 channels; 80 channels are available in each band. A license is required for operation, which stipulates the use of a specific pair of frequencies and grants exclusive usage of the frequency pair within a 70-mile radius, reducing interference from other users. This is a data-only band and there are no voice users and no antenna height restrictions. This band permits up to 5 W transmitters. Data transmission speeds are available up to 9.6 kbps.

960 MHz Point-to-Point This is a data-only band that provides secure data channels that are often used for backhaul applications. Transmitter power is limited to 5 W and the available bandwidth is typically between 768 kbps and T1 rates. There are no antenna height restrictions. Propagation is generally line of sight at this frequency and foliage can attenuate the signal.

Unlicensed Bands

The FCC created the industrial, scientific, and medical (ISM) bands in 1985 (in the code of federal regulation CFR 47, part 15.247). Instead of using fixed channels like the VHF and UHF bands, the FCC allowed multiple users to use most of the band with spread spectrum techniques. In the ISM bands, unlicensed radios must use frequency-hopping or direct sequence spread spectrum techniques, limit transmit power to 1 W or less, and emit no more than 36 dB referenced to 1 mW (dBm) of power. The ISM bands defined by the ITU-R and FCC include

- 902–928 MHz (Region 2 only)
- 2.400–2.500 GHz
- 5.725–5.875 GHz

Unlicensed radios are widely available. However, there is no guarantee of interoperability between manufacturers. Unlike Wi-Fi routers, spread spectrum radios are not necessarily based on IEEE 802 standards, even though some IEEE-based products use spread spectrum technology. Since spread spectrum radios use proprietary techniques, it is unlikely that radios from different manufacturers will work together; even different models of radios from the same manufacturer may not work together.

One distinct advantage of unlicensed radios is that implementing repeaters to extend coverage is fairly easy. Because there are no fixed channels, additional channels can be easily created on the fly simply by changing the radio configuration. Unfortunately, the RF noise floor increases as local use increases. This is especially a problem in the 2.4 GHz band.

Effective Isotropic Radiated Power Effective isotropic radiated power (EIRP) is limited to 36 dBm, the equivalent of a 1 W transmitter using a 6 dB isotropic (dBi) antenna with no feed line losses. Maximum transmitter power must be limited to 1 W or 30 dBm at all times. The antenna gain can be increased to compensate for feed line losses as long as the EIRP remains below 36 dBm. If the antenna gain is more than 6 dBi greater than the feed line losses, the transmitter power may need to be reduced so as not to exceed 36. If the antenna is rated as a half-wave dipole (dBd), then 2.15 dB must be added to adjust dBd to dBi. FCC mandates a professional installation in reporting EIRP. The formula to calculate EIRP is as follows:

$$\text{Xmit} + \text{Antenna gain} - \text{Feed line loss} \leq 36\ \text{dBm}$$

Antenna gain is in dBi and

Feed line loss is in dB

The FCC does not limit antenna height in this band, though other factors may apply, such as local ordinances and Federal Aviation Administration rules around airports and hospitals. Some radios use separate receiving and transmitting antennas. In this case, there is no limit on receiving antenna gain, which can be useful to extend the radio path beyond what is normally possible with a shared transmit/receive antenna.

Spread spectrum radios have a shorter effective range than licensed systems, primarily because they operate using only 1 W or less. Because the output power is so low, an RF study is highly recommended to ensure system operation and to properly locate the master radio.

Spread Spectrum

Spread spectrum is a modulation technique, which spreads the transmitted signal over a much larger frequency bandwidth. Fundamentally, spreading a signal over many narrowband "noisy" channels decreases the signal-to-noise ratio and increases the probability that the signal will be received with little or no interference. Lower power may be used over a larger range of frequencies as opposed to a high-power signal over narrow ranges, which has a direct effect on the noise. Noise is an integral component of the signal in the form of other frequencies, which are multiples of the base or the carrier frequency. Using lower power decreases the effect of these multiples, as well as the effects of other noise components due to atmospheric factors. Also, the information is spread over a large number of frequencies, allowing the system to ignore noise specific to each narrowband frequency channel. The effect of this technology is to produce secure and reliable wireless communication while dramatically increasing system capacity over previous systems. Two main types of spread spectrum are in use: direct sequence spread spectrum (DSSS) and frequency-hopped spread spectrum (FHSS).

Direct Sequence Spread Spectrum DSSS is an all-digital system using pseudorandom or pseudo-noise (PN) codes to control frequency spreading. These codes are labeled "pseudo" because they are not actually random or noise. The information to be transmitted is modulated with the PN code. Modulation techniques in use are binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK).

DSSS spreads RF power over a wide bandwidth. The PN or Barker code is merged with the data using an exclusive OR (XOR) function, resulting in a stream with the same rate as the PN. In the receiver, the PN is used with an XOR function to recover the data.

Process gain is realized when the bit rate is below the spreading rate (i.e., each bit gets more than one frequency to try). Process gain is the ratio of spread compared to the unspread signal.

DSSS is generally better than FHSS for high bit rates because each bit has multiple frequencies to avoid interference. Also, broadband noise does not affect the signal until it swamps it entirely, although the data rate may suddenly fall to zero when that happens.

Frequency-Hopped Spread Spectrum FHSS also utilizes PN codes to spread transmitted data but is the easier of the two main spread spectrum methods to implement. The technique employs precision frequency synthesizers, which continuously shift the center carrier frequency based upon the impressed PN code

The period of time a signal remains on a specific channel is called the dwell time. The dwell time is typically very brief, less than 10 ms. The manipulation of dwell time is very effective in eliminating interference to other users. FHSS transmits very few (i.e., less than 2) data bits, which allows improved data detection at the receiving end. If a frequency is blocked or jammed, however, data may be lost, requiring the use of error correcting codes. The FHSS radio transmits a few bits and then changes frequencies within 400 ms. The receiver can change frequencies at the same time as the transmitter because they are synchronized and have the same PN code. The radio is not permitted to return to the same channel in less than 25 hops at 900 MHz, 15 hops at 2.4 GHz, or 75 hops at 5.8 GHz.

Since users operate on nonexclusive frequencies, some interference must be expected and considered normal. Therefore, radios are designed to manage the effects of interference by avoiding frequency bands, changing hopping sequences, and sending small data packets with automated retries. To reduce interference, some radios allow groups of problem frequencies to be skipped. Because the radios are unlicensed, there is no recourse against interference; users must tolerate interference from other users. During installation, be careful to avoid using default network address settings since other users may be within range.

FHSS enables multiple users to share the same band with minimal interference. If a hop channel is jammed, the data transmit on the next hop. The entire band must be jammed before communications ceases. Noise generally only affects individual hops. As noise increases more and more, hops become ineffective and the data throughput proportionately degrades gracefully. Because of this, FHSS is considered more robust than DSSS.

902–928 MHz Spread spectrum radios in the 900 MHz band are popular because of their ease of use and license-free status. These radios operate in a data-only band and have communications speeds up to 19.2 kbps. This band generally has lower bandwidth than the 2.4 GHz band but has less interference. This band is unique to the United States and other ITU-R region 2 countries (e.g., the Americas, Greenland, and some of the eastern Pacific Islands) and some non-region 2 countries (including Australia and Israel). In other areas, the cellular global system for mobile 900 MHz (GSM-900) band overlaps this band.

Some of the benefits of this band include moderately good area coverage; 900 MHz penetrates through obstructions like walls and buildings better than higher frequencies and can propagate for several miles. Since it bends around obstacles to a certain degree, the term near line of sight (LOS) is used. There are no antenna height restrictions within 902–908.75 and 918.75–921.75 MHz. Height is limited to 49 ft and power is limited to 400 mW from 908.75 to 918.75 and from 921.75 to 928 MHz.

Other users in this band include

- Location monitoring systems
- Cordless phones
- Some military radar
- GSM-900 cellular (in countries that use this band)

2.4–2.4835 GHz This band is available in most major world markets, unlike 900 mHz, which is available primarily in the United States. In the United States, output power is limited to 1 W EIRP. Output power is limited to less than 100 mW in Europe.

The data rate of this range is up to 1.544 Mbps, which is higher than 900 MHz bands. There are no antenna height restrictions, but due to the higher frequency, more signal attenuation from items such as trees should be expected than at 900 MHz.

There are many other users in this band, including

- Microwave ovens at 2.45 GHz
- Cordless phones
- IEEE 802
- Wi-Fi (802.11b)
- Bluetooth (IEEE 802.15.1)—low power (100 mW max)
- IEEE 802.11g
- ZigBee (IEEE 802.15.4)—low power
- IEEE 802.11n
- WiMax (IEEE 802.16e)—range up to 25 miles
- Baby monitors
- Car alarms

5.725–5.85 GHz This band belongs to both the ISM bands and the unlicensed nation information infrastructure (U-NII) upper band created in 2004. Transmitter power ranges up to 1 W in the United States; other U-NII frequencies are limited to less than 250mW. Bandwidth is large.

There are relatively few users in this band, including

- Cordless phones
- IEEE 802.11a—range up to 390 ft
- IEEE 802.11n—range approx 820 ft

Radio Repeaters

Repeaters can be purchased prebuilt or can be pieced together from standard transceivers. A typical repeater system configuration is depicted in Figure 16.3. Repeater radios should be rated for continuous duty. Many transceivers designed for remote sites are not recommended for continuous use. Repeaters can be constructed from two licensed radios operating on different channels, a licensed radio and a spread spectrum radio, or two spread spectrum radios on different networks. Pairing a licensed transceiver with a spread spectrum transceiver is a common configuration for providing coverage for a cluster of sites in a remote area.

A repeater uses a Yagi antenna pointed to the central radio and an omnidirectional antenna to serve the local remote sites. These antennas can share the same tower but must be separated vertically to minimize mutual interference. Repeater antennas should be located in a high and central location to provide a large coverage area.

A central repeater configuration can be used in cases where the master radio is not in a good location to directly communicate with all remote sites. A repeater is placed in a location that can reach the central and remote sites. The master radio talks through the repeater to the end sites. If only one site is out of reach, a tail-end repeater can be used to connect that site with the rest of the radio system.

Radio repeaters are useful when site A can communicate with site B, and site B can communicate with site C, but site A cannot communicate with site C. Radio repeaters come in two main forms: *non-buffering repeaters* and *store and forward repeaters*.

A *non-buffering repeater* requires two transceivers, receiving a transmission on one frequency and reproducing it on another with virtually no delay. A communications cable connects the receiver in radio A to the transmitter in radio B and vice versa. Whatever is received is transmitted on the other channel.

A *store and forward repeater* only requires one transceiver and some data storage. The repeater receives a transmission and temporarily stores it in a data buffer, which can be in the radio or in a local controller. When the channel is quiet, it retransmits the information often on the same frequency on which it was received. Packet radios are generally store and forward repeaters. Each site is usually equipped with an omnidirectional antenna to provide coverage to multiple sites. A delay occurs each time the data are buffered and retransmitted; this can be a second per hop. If many hops are required for communication, real-time control becomes very difficult because of the time delay. These radios are well suited to automatic meter reading systems

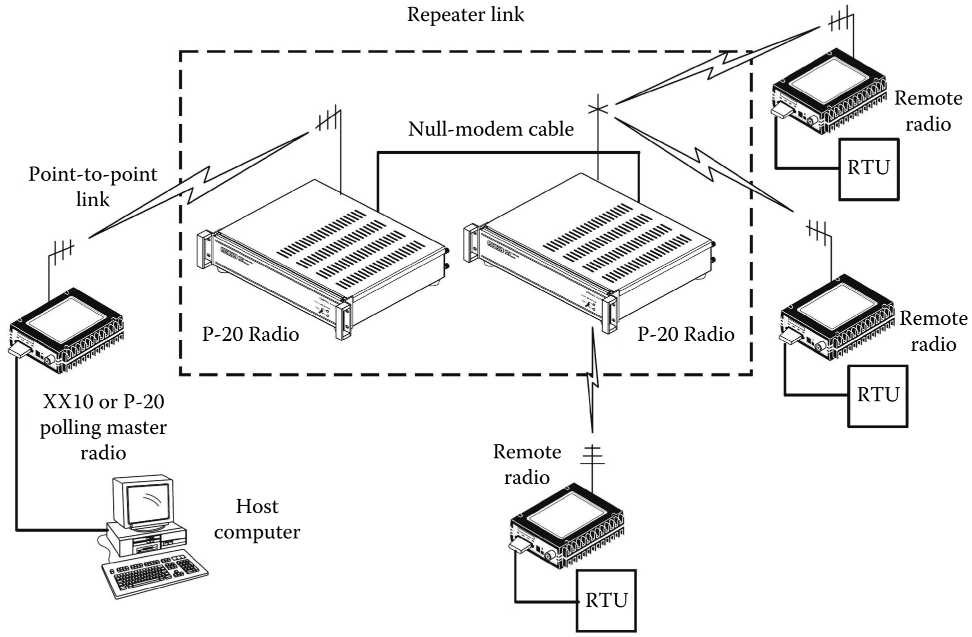

FIG. 16.3
Repeater system configuration. (Courtesy of General Electric, Fairfield, CT.)

TABLE 16.2

Length vs. Loss in Coaxial Cables at 900 MHz

Cable Type	*10 ft (3.05 m), dB*	*50 ft (15.24 m), dB*	*100 ft (30.48 m), dB*	*500 ft (152.4 m), dB*
RG-8A/U	0.85	4.27	8.54	42.70
1/2 in. HELIAX	0.23	1.15	2.29	11.45
7/8 in. HELIAX	0.13	0.64	1.28	6.40
1 1/4 in. HELIAX	0.10	0.48	0.95	4.75
1 5/8 in. HELIAX	0.08	0.40	0.80	4.00

Source: Courtesy of General Electric, Fairfield, CT.

and other data collection systems where speed is not the main criteria.

Attenuation Unlike hardwired or fiber-optic systems, radios radiate their power over a large area. In LOS frequencies, radio waves travel in a straight line from the antenna. They do not bend around corners, nor do they follow the curvature of the earth. LOS becomes dominant with higher frequencies, especially near or over 1 GHz. At lower frequencies, radio waves bend somewhat around objects and travel farther over the horizon.

Free space attenuation occurs because as the signal moves away from the transmitter, the area of the sphere it forms grows exponentially faster than the distance.

Rain and foliage also cause path attenuation, which becomes more of a problem at higher frequencies. Foliage in general decreases radio signal strength; at certain frequencies, pine tree needles absorb RF energy, especially if they are wet.

Attenuation occurs before the signal gets to the antenna because of feed line and connector losses. Feed line losses are stated as a dB loss per foot of cable at a given frequency, provided by the cable manufacturers (Table 16.2).

Fade Margin Fade margin allows for reduction in signal strength caused by multipath interference, slight antenna movement, and changing atmospheric conditions. System reliability is directly related to fade margin, but so is system cost. SCADA systems typically use a fade margin of 20–30 dB above receiver sensitivity.

Radio Topologies

Point-to-Point Point-to-point is easily implemented with radios. Since only two points are needed for the radio path, directional antennas can be used to maximize the signal strength. Both sites can use Yagi antennas to focus the signal and minimize interference from other sources. Because of this, the radio path quality is better than other topologies, which is why the maximum distance that manufacturers claim is usually a point-to-point link.

Point-to-Multipoint Point-to-multipoint can be implemented with spread spectrum radios or a frequency pair for licensed radios. When using unlicensed spread spectrum radios, the central radio is configured as the master and transmits in all directions using an omnidirectional antenna. The remote sites use Yagi antennas aimed toward the central site and only respond to the central radio but not the other remote sites. It may be difficult to locate the central radio so that it has good communications to all the end sites. If this is the case, using a centrally located repeater can often solve this problem.

Peer-to-Peer Peer-to-peer networks, also known as wireless mesh networks, provide a flexible communications system. Each node can send and receive data and can route messages to its neighbors using store and forward techniques. A main advantage of this network is that the paths between sites are physically shorter than in other topologies since a radio only needs to be able to communicate with its neighbor.

Peer-to-peer is implemented with packet radios, the most common of which is the Ethernet radio. All radios in this topology use omnidirectional antennas and can be configured as store and forward repeaters. A routing algorithm in each radio directs the packets toward their destination. When a packet is ready to be sent from a remote site, the packet's destination is encoded in the header of the packet. The radio picks a neighboring radio in the correct direction that has communicated successfully in the past, and the remote radio then transmits the data packet to that radio. When the radio receives the packet, it may determine that it is not the final destination for the packet. It then looks for a neighbor in the correct direction and forward the data packet. This repeats until the data arrive at its final destination where an acknowledgment of receipt is then sent back through the radio network to the original remote site. It is commonly held that bigger networks are better because there are more communication paths. In practice, this is only true to a point; as the network grows larger, more attention must be paid to bottlenecks and data paths. If multiple users exist, some coordination of radio resources should take place. Without some coordination, the network can become overloaded and suddenly stop passing data.

Hop delays and the number of hops directly affect the overall network speed. This topology may not be a good fit for time-sensitive data and control applications unless the number of hops is very low and overall network delays are small.

CELLULAR TELEMETRY

We know mobile wireless telephones as the "cell phones" because of the technology that makes their use possible. The theory behind cellular telephones is simple, but the actual implementation is more difficult. The problems of the efficient use of available channels, power and size of mobile units, and connection to the wired telephone network had to be addressed and dealt with before any attempt could be made to implement mobile telephone service for the masses.

Early in 1981, a new mobile telephone standard was introduced. Called the advanced mobile phone service, it was the first system to use the concepts of cells and frequency reuse. Cells are defined as the area of coverage of a given base station and can cover from 2 to 10 miles depending on location. Cells are represented by hexagons for planning and statistical purposes. The true shape of the covered area may be completely different depending on the physical terrain of the cell. The optimum shape for a cell is a circular pattern of transmission coverage. The comparison of ideal and actual cell coverage is illustrated in Figure 16.4.

Without the technique of frequency reuse, cellular telephones would not be possible. Each cell is assigned a specific number of channels (i.e., frequencies) to cover mobile units in that cell area. As a user travels from cell to cell, the user is switched into another channel, freeing up the previously used channel. Sophisticated switches called mobile telephone switching offices (MTSO) connect the cell site to the wired telephone network and to other cell sites. The terms "cell site" and "base station" are used interchangeably; both terms describe the radio transmitter that serves the cell. In addition to frequency reuse, multiplexing techniques are used to allow a higher concentration of calls over a given channel. The multiplexing techniques used are similar to those used in wired telephone technology. Fiber optics has also allowed a larger volume of calls to be completed reliably. Most cell sites are connected to the MTSOs using fiber optics. All connections between MTSOs and the switches of the wired system are T1 and run over a fiber-optic trunk.

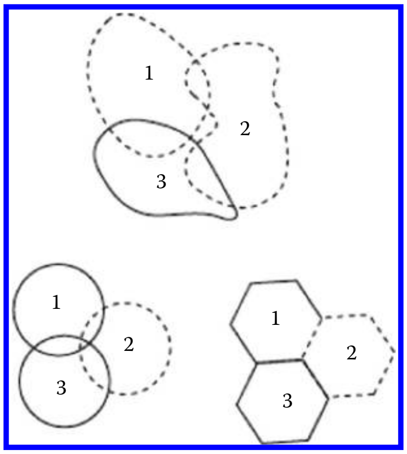

FIG. 16.4
Idealized vs. actual cell coverage.

Channels and Clusters

Control channels carry information, which controls the operation of the telephone, and are integral to the efficient use of available frequencies. Each cell has two control channels, one for each system. The mobile unit monitors one of the two frequencies for information needed to initiate or complete a call. Control channels are used to set up the call; the actual conversation takes place on a voice channel. The control channel in each cell is usually the first channel assigned to the cell.

Frequency reuse is the underlying principle of cellular communications. The same bands of frequencies can be reused in different cells, allowing the most efficient use of the frequency spectrum. Each cell may support up to 45 voice channels and has one control channel assigned to it. Channels are assigned to cells to arrange the maximum geographic distance and assure channel separation. As a mobile travels from one cell to another, the circuit is automatically switched to another channel in the adjacent cell. Continuing through several cells, a mobile telephone may be switched to many different channels without any perceptible interruption in service.

Cells are generally grouped into clusters. In less congested areas, a 12 cell cluster, or frequency reuse pattern, is used to handle all traffic. A typical cluster is seven cells. Figure 16.5 illustrates an idealized seven-cell cluster.

A cluster utilizes 42 channel sets, 21 for each system. All data will pertain to the total system channel capacity of 832 channels. Each cell is assigned six channel sets, each channel separated from another by seven channels. No frequency pair is reused within the cluster. In an adjoining cluster, channels are similarly assigned. This method of channel assignment and physical separation of cell sites is employed to avoid any occurrence of cross-channel interference.

Cells can be further broken into sectors. In the example discussed earlier, an ideal cell was illustrated. An omnidirectional antenna is used to transmit in all directions outward

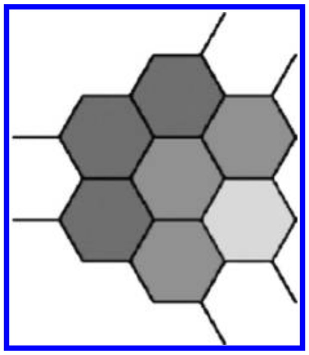

FIG. 16.5
A seven-cell cluster.

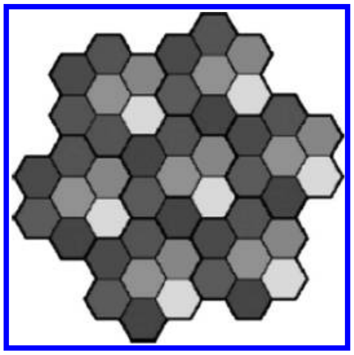

FIG. 16.6
Frequency reuse patterns.

from the base station. Within the cell, a mobile unit uses the assigned channel until it is handed off to another cell and assigned another channel. Using directional antennas, cells may be separated into three or six sectors depending on the number of antennas used. The effect of sectorization is to provide much better coverage in the cell. Theoretically, the amount of traffic handled is also increased. A disadvantage is the greater chance of cross-channel interference.

Frequency reuse is only possible with the careful assignment of frequencies and channels to cells that are separated by adequate distances. Figure 16.6 illustrates typical cell frequency reuse patterns based upon the seven-cell cluster. Ideally, this is the smallest possible distance.

The larger the number of cell sites in a given geographic area, the greater the chance for interference. The minimum practical size for a cell is a coverage area of about a mile. Tunnels, bridges, and highly congested urban areas are often served by "microcells," which may be up to 300 m in diameter. Picocells are even smaller covering an area of only 30 m. Picocells can be used in offices or college campuses in wireless networking applications. At the high end, a cell could be as much as 35 miles in diameter, the major constraint being the transmitting strength of the mobile unit. Other factors affecting propagation are trees, hills and valleys, mountain ranges, and buildings. At present, cellular telephones are limited to a maximum radiated power of 7 W. This power is referred to as the effective radiated power. Larger cells do not depend as much on frequency reuse as do smaller cells. This is a direct consequence of the amount of traffic in the coverage area of a cell. As traffic increases in a given area, cells are split and clustered to take advantage of frequency reuse.

Multiplexing

In cellular telephony three common multiplexing techniques are currently used:

1. Frequency division multiple access (FDMA)
2. Time division multiple access (TDMA)
3. Code division multiple access (CDMA)

FDMA is widely used in analog systems and is being replaced by the latter two techniques, which are more suitable for use in digital systems. Aside from providing advanced features such as caller ID, digital telephony does not provide any great advances in technology. Coupled with advanced multiplexing techniques, however, it allows marked increases in cellular frequency use efficiencies. TDMA is used with analog systems as well as the newer digital systems. CDMA is, by definition, a purely digital system.

FDMA FDMA was the first technique used for increasing the capacity of available cellular channels. Each 30 kHz cellular frequency was broken into three 10 kHz subchannels over which voice was transmitted.

TDMA TDMA is another multiplexing technique used to increase frequency use efficiency. In TDMA, each narrowband subfrequency is divided into six repeating time slots or frames. Two slots in each frame are assigned to each call. TDMA suffers from "multipath fading" and distortion, phenomena that are caused by reflections of the signal from any number of physical interferences. These reflections cause interference and distortion because of time differences in the arrival of the signal from different paths. Fading is caused by the same physical interferences. Enhanced time division multiple access (ETDMA) makes even more efficient use of the frequency spectra. ETDMA actively monitors a conversation, sensing pauses or dead spots in the communication. The system utilizes these holes in the transmission and replaces them with bits from other conversations. This system is not universally used; however, this technique makes the most effective use of the available time slots.

CDMA CDMA is the latest method for improving spectral efficiency. CDMA works by assigning a unique code to each message and then transmitting the encoded message over single or multiple frequencies. By using this method, channel efficiency can be increased by a factor of 20. This is a vast improvement over FDMA and TDMA, which allow up to a maximum of 6 to 1 improvement in channel efficiency. The principles of CDMA are well known, as they have been used in military communication for the last 35 years. Chief among the advantages of CDMA are its excellent immunity to noise and improved security from interception.

Digital Cellular Data

Current 2.5G and 3G technologies offer generous bandwidth to telemetry applications that used to be limited to 56 kbps modems. However, since most telemetry applications are designed to be small and efficient with data, there is not a strong need for the increased bandwidth. In the United States, two distinct systems exist: *Global system for mobile communications* (GSM) and CDMA.

Global System for Mobile Communications GSM 2.5G technology is general packet radio service (GPRS) with data rates up to 85 kbps and the 3G technology is enhanced data rates for GSM evolution (also called EDGE) with data rates up to 200 kbps.

GPRS is a data service that can be deployed on either GSM or TDMA systems. GPRS facilitates instant connections whereby information can be sent or received immediately. High immediacy is a very important feature for time-critical applications where it would be unacceptable to wait even an extra 30 s.

With GPRS, the information is split into separate but related packets before being transmitted and reassembled at the receiving end. The Internet itself is another example of a packet data network. Packet switching means that GPRS radio resources are used only when users are actually sending or receiving data. Terminals that support GPRS are required at each site.

Code-Division Multiple Access CDMA 2.5G technology is one times radio transmission technology (1×RTT) with data rates up to 153 kbps and 3G technology is evolution data optimized (EVDO) with data rates up to 300 kbps. 1×RTT technology supports both voice and data services over a standard (i.e., 1×) CDMA channel. It provides wireless Internet services at peak data rates of up to 153 kbps. Terminals that support CDMA are required at each site.

Topology

Because digital cellular is a packet-based system, peer-to-peer is the native topology for cellular. Using the proper protocol, a virtual point-to-point or point-to-multipoint network can be constructed.

SATELLITE TELEMETRY

A satellite is any natural or artificial body that describes an orbit around another body. In this discussion, satellites will be defined as man-made objects that orbit the Earth in the space surrounding it. These satellites are capable of a variety of tasks, from military missions to direct broadcast television. Until recently, the concept of satellite networking was just that, a concept. With the advent of affordable cellular technology, the need for a mobile method of communication and networking had been satisfied, at least as long as one was within range of a cell. Satellite networking has become a new means of mobile connectivity to expand networking capability further, particularly to those areas where it would be difficult or impractical to provide wired or cellular service, such as at sea or in the air. Future wireless networks will rely heavily on satellites for coverage of areas that were heretofore unable to obtain coverage. Advances in this technology will enhance existing cellular networks. Remote monitoring and control of facilities will not only become more feasible and reliable, but also much less costly to operate and maintain.

Satellite networking is ideal for sites greater than 20 miles apart or whose terrain obstructs the path to the central location but does not block the view to the satellite.

Network operation centers (NOCs) use a large parabolic dish antenna up to 11 m. The NOC handles all communications to and from the satellite. Communications are packet based. TDMA is used for inbound traffic and TDM is used for outbound.

Systems are arranged in either a single or double hop arrangement. The double hop generally has twice the latency of a single hop. All satellite systems have propagation delays. The higher the orbit, the more the delay is realized. For example, a geosynchronous satellite has a round trip delay of more than 500 ms because of the great distances (e.g., over 20,000 miles) traveled. For a slow process, this may not be a problem.

Basic Satellite Technology

Artificial satellites are unlike aircraft in that there is very little control over the route on which they fly, or orbit. Satellites typically move about the Earth in elliptical or circular orbits. The altitude of orbit can be adjusted by the amount of force used to launch the object from Earth; this altitude has a profound effect on the time it takes for the satellite to orbit the Earth, called the *period*. Modern communication satellites are found in many different orbital positions, each with a characteristic period.

Satellites stay in orbit because of the interaction between several natural forces. Gravity is chief among them, exerting a constant attractive force upon the orbiting object. Counteracting this gravitational pull is centrifugal force. Centrifugal force acts upon any object moving in a circular motion, forcing the object to move away from the center of its rotational plane. For any object, this force is proportional to the square of its velocity. In actuality, the orbiting object is continuously falling into the Earth, the object's *angular velocity*, or sideways motion, acting to move it out of the way of the Earth before it collides. Centrifugal forces acting on the satellite compensate for the gravitational force also acting on the object, allowing it to remain in a predetermined orbit above the Earth as long as the angular velocity remains constant.

The laws describing planetary motion were explained by the work of Johannes Kepler, whose three laws of planetary motion are the basis for the understanding of satellite orbital mechanics (Figure 16.7). Kepler's first law states that the planets orbit the sun in an elliptical path, with the sun occupying one focus of the ellipse. Applying this to an artificial satellite, the object's path can be described as elliptical, with the Earth occupying one foci of the ellipse. This means that the distance between the sun and the planet is constantly changing.

Kepler's second law states that the area swept by a straight line from the center of the sun to the center of the planet sweeps equal areas in equal time periods. The angular velocity of the planet is constantly changing as it traces its orbit. In

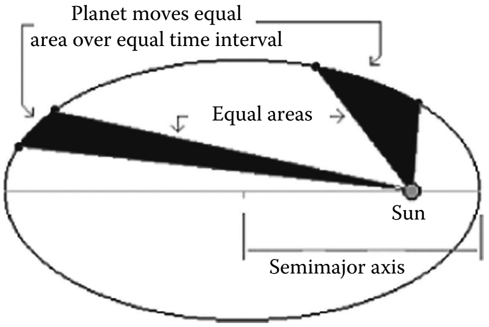

FIG. 16.7
Kepler's laws illustrated.

other words, the orbit of a body is moving more slowly at the apogee of its orbit, the point furthest from the Earth, than at its perigee, the point closest to the Earth.

Kepler's third law states that the squares of the planets' orbital periods are proportional to the cubes of the semimajor axes of the orbits. Simply put, if an object's orbit (i.e., height above the Earth) is known, then the object's orbital period can be determined; the converse is also true, allowing one to determine orbit if the period is known.

The major thrust of Kepler's laws is to establish that planets or satellites travel at different speeds during their orbit; these laws allow the accurate measurement or prediction of these speeds. This information is especially useful in planning and implementing a satellite system. By manipulating the orbit of a satellite, the period can also be manipulated, allowing a large degree of control over coverage areas.

Satellite Orbits

Low Earth Orbit Satellites Low earth orbit satellites (LEOS) orbit between 500 and 4000 km (300 and 2500 miles) above the Earth. LEOS complement the terrestrial cellular systems and are based on small lightweight satellites, which are less costly to build and place in orbits. Because these satellites are close to the Earth, low-power transceivers can easily communicate with the nearest satellite. Coverage area is small for a particular satellite and comprehensive coverage requires multiple satellites with overlapping "cells" similar to the method of coverage used by terrestrial systems. Because of the much shorter distances to be covered by the signals involved, users can communicate using inexpensive handheld devices, such as what is commonly referred to as "sat phones."

Different systems have been proposed, each using a different number of satellites, referred to as a *constellation*, to effectively provide coverage to the entire surface of the Earth. Proposals range from a system of 840 satellites in 21 orbital planes, with 40 satellites to a plane, to a system of 288 satellites in 12 planes, with 24 satellites to a plane. The satellites would orbit the Earth at a speed between 16,000 and 17,000 miles/h, with a period of approximately 90 min. The distributed nature of the system offers superior reliability over a fixed satellite. If a fixed or single satellite is damaged or malfunctions, the entire network can be rendered inoperative, but redundancy makes this unlikely. LEOS offer multiple satellites and therefore redundant equipment and signal paths.

Little LEOS and Big LEOS A little LEOS is a small, low-cost satellite weighing between 50 and 100 kg. Little LEOS systems have been allocated the bands of 137–138 and 400.15–401 MHz for downlinks and 148–149.9 MHz for uplinks. These bands have been used for meteorological satellites, general research, and fixed and mobile communication systems, slow data communication, paging, and messaging systems.

Big LEOS, with satellites weighing between 350 and 500 kg, are aimed at data communications and real-time voice into handheld units. A new allocation of spectrum between 1610 and 1626.5 MHz, currently used by aeronautical radio navigation services, are used to implement this system. Big LEOS can carry voice and high-speed data services, unlike little LEOS. Also, big LEOS use new technologies such as onboard processing and inter-satellite backbone linking at millimetric (30 GHz) frequencies.

Iridium, a little LEOS system built and implemented by Motorola placed 66 satellites into orbit before declaring bankruptcy. Big LEOS holds the most promise for universal connectivity, touting itself as the "Internet in the sky." For comparison, signal latency, the time it takes for a signal to make the round trip from Earth to the LEOS and back, is only 20–40 ms as opposed to upward of 0.5 s for a geosynchronous earth orbit satellite (GEOS). Demand for LEOS services is expected to be primarily in rural telephone service, mobile, and broadband data communication.

Medium Earth Orbit Satellites *Medium earth orbit satellites* (MEOS) operate in the range of 8,000–16,000 km (5,000–10,000 miles). While offering greater area coverage than LEOS systems, the distances involved require larger terrestrial transceivers. Also signal latency for MEOS is in the range of 50–150 ms. MEOS are often used as space-based relays, operating in conjunction with GEOS systems.

Geosynchronous Earth Orbit Satellites GEOS systems offer the distinct advantage of being able to be "parked" at a specific location over the Earth's surface. GEOS operate at an orbit of 35,860 km (22,282 miles) above the Earth. Theoretically, three satellites in geosynchronous orbit above the equator could cover the Earth's entire surface, with the exception of the Polar Regions. Allowing for the agreed-upon 2° separation between satellites, a possible constellation of 180 satellites could be parked above the equator. Given the distances involved, however, transceivers capable of communicating with GEOS systems are land based and usually not mobile. Signal latency approaches 0.5 s on a round trip between Earth and the satellite.

Figure 16.8 illustrates the orbits of LEOS, MEOS, and GEOS.

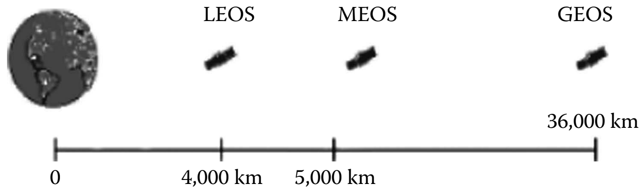

FIG. 16.8
Comparison of satellite orbits.

Communication Bands

Satellite communication occurs within four allocated bands of frequencies: the L, C, Ku, and Ka bands. One of the problems facing the industry is finding space within the allocated frequency spectra. Most of the available band is already allocated to other services, which have to contend with a large installed base of equipment designed to operate in the allotted bands.

L Band Communication occurs within the spectrum at frequencies between 1.53 and 2.7 GHz. This range of frequencies is a "long" wave and is capable of penetrating many structures and materials. Less powerful transmitters may also be used. This band is allocated to existing services, leaving very little space for new satellite communication services.

C Band The C band has traditionally been used for the direct broadcast television market. Although this is still the primary use for this frequency band, the market is being supplanted by digital satellite systems. C band systems utilize large (e.g., 7.5 ft) diameter antennas to capture the relatively weak signals from the geosynchronous satellites used.

Ku Band The Ku band operates in the range of frequencies between 11.7 and 12.7 GHz (downlink) and 14.0 and 17.8 GHz (uplink). This medium wave transmission also has good penetrating power and, owing to the large bandwidth per channel, can carry quite a heavy data. This band is also largely allocated to existing services.

Ka Band The Ka band operates between 18 and 31 GHz; wavelengths are referred to as "millimetric." Although there is an abundance of available spectrum, the signals do not have the same penetrating power as the longer wavelengths and are subject to fading, particularly from atmospheric conditions such as rain and snow. Also, much more powerful transceivers are required to affect reliable communication.

Satellite Networks

Satellite networks operate much the same way as any other network, with the major difference in the type of equipment used to convey the signals. Practical wireless networks use a combination of terrestrial systems such as existing cellular and wired networks, which connect through Earth stations to an available satellite. One unique facet of satellite networking is the methods of signal routing developed to deal with the requirements of a space-based system.

Routing Two types of routing are in common use: bent-pipe routing and satellite-to-satellite routing. In bent-pipe routing, a user sends a signal to the nearest satellite, which reflects the signal back to Earth to either the intended receiver or an Earth station. The signal is then routed on conventional terrestrial wireless (i.e., cellular) or landlines to another Earth station. The signal is then uplinked to another satellite, which then finds the intended receiver and downlinks the signal, completing the network transaction.

Satellite-to-satellite routing involves transmission of an uplinked signal to several other satellites, each of which attempts to find the intended receiver. The closest satellite then downlinks the signal. Within the satellite constellation, however, a method of inter-satellite linking (ISL) must be established to affect the orderly transfer of information between satellites. These methods of ISL are accomplished in two ways: *interorbit* and *inter-satellite*. Interorbit linking involves the transfer of information between satellites in different orbital planes. Interorbit linking has the capability, when fully implemented, to eliminate the need for a terrestrial link, as in bent-pipe routing. Inter-satellite linking is simply communication between satellites in the same orbital plane.

Protocols Satellite communication and networking makes extensive use of existing multiple-access protocols. Among these protocols are TDMA, CDMA, and FDMA.

Satellite Networks Topology

Peer-to-peer is the native topology because satellite systems are digital packet-based forms of communication. Using the proper protocol, a virtual point-to-point or point-to-multipoint network can be constructed.

CONCLUSION

There is a wide selection of systems available that can be used for telemetry applications. Different telemetry technologies have advantages and disadvantages and many factors must be balanced for successful communications systems and there is no "one size fits all" solution. This becomes apparent as remote sites become numerous and cover a wide area; what works best in a city, may not work well in the countryside.

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